EXPERIENCE WITH LIFE ASSESSMENT AND REFURBISHMENT OF 400 kV SHUNT REACTORS

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ABSTRACT

Seven 400 kV shunt reactors were refurbished while under field conditions. The overall objective of the refurbishment program was to extend the life of the reactors from the 25 years to 35 - 40 years and to reduce the costs of both operation and maintenance. This paper will offer an approach to the creation of a life extension program and will present the experiences gained from the implementation of this program. Evaluations of the reactors' conditions both before and after refurbishment are also provided.

INTRODUCTION

All of the subject shunt reactors have the same nameplate parameters: single phase, 55 MVAR, $420/\sqrt{3}$ kV, 227 A, 1450 kV BIL, 65°C rise, OFAF (two working and one reserve 160 kW heat exchangers), open breathing through silica-gel filter. Reactors were manufactured in 1971 by "Electrozavod" of Moscow and were installed in two 400 kV substations in the Czech Republic. The expected life of these reactors was specified at 25 years. In 1993, the important decision of either replacing these reactors or extending the reliability life span by 10-15 years was required.

The life extension program's objectives were outlined as follows:

- Extend life up to 35-40 years.
- Improve reliability, serviceability, and controllability.
- Reduce costs of operation and maintenance.

All of the shunt reactors had the following design features (Figure 1):

- Shell-type, electromagnetic system comprised of eight C- shape yokes and non-magnetic central leg.
- Disc type 400 kV winding.
- Oil-barrier main insulation between the winding and grounded yokes with electrostatic shield attached to the last barrier that faces the yokes.
- Top and bottom aluminum electromagnetic shields to protect the tank from overheating due to stray flux.
- Oil-impregnated condenser 400 kV bushing with semiconducting paper layers. The bushing is installed within the winding and is designed to operate under a strong magnetic field.

The operating conditions were as follows:

- Rated load was carried out nocturnally and during weekends.
- Systematic high temperature fluctuations were causing an ingress of water and air into the tank.
- Frequent switching transients.

1 - winding
2 - magnetic shunt
3 - tank
4 - bushing
5 - pressboard barrier (oilbarrier insulation)

6 - electrostatic shield
7 - electromagnetic shield
8 - porcelain support

Reactor RODC - 55000/400
FIGURE 1

The life extension program included the following:

- Analysis of service experience.
- Evaluation of design reliability.
- Definition of a refurbishment program.
- Definition of a processing program and technology of an overhaul.
- Test and quality assurance.

LIFE EXTENSION PROGRAM

Analysis of Service Experience

Service experience with twenty 500 kV sister units and 430 similar units was compiled and analyzed to establish probable "weak points". Over the period of 1976 until 1992, the failure rate was calculated to be approximately 1% [1] . The following failure modes were noted:

- Flashover along the winding and traces of discharge on the barrier facing the winding.
- Flashover between two or more coils.
- Flashover along the inner surface of the lower bushing's porcelain.

In several cases, severe insulation contamination consisting of metallic particles was detected. In certain cases, wearing of the pump bearings and aluminum shield attrition were noted as sources of particle generation. Also in some cases, an elevated water content in the insulation contributed to failure.

Evaluation of Design Reliability

The reactor's design "weak points" were assessed by re-estimating the acceptable margins through modern knowledge and methodology. To achieve this, the following analyses were performed:

- Calculation of impulse voltage distribution along the winding; estimation of dielectric strength margin with the presence of a switching surge and lightning impulse.
- Calculation of temperature distribution in the winding; determination of hot spot levels; optimization of cooling capabilities.
- Calculation of the distribution of current and losses in electromagnetic shields; evaluation of mechanical stress on the shields.
- Calculation of electrical fields within the bushing considering the effects of the reactor winding; estimation of the dielectric strength margin.

Dielectric Stress

Some of the results from analyses are shown in Table I. The dielectric strength along the winding was found to be a "weak point". It was determined that a minimal margin of 17% could be drastically reduced in cases where contamination with conducting particles had occurred.

TABLE I
Dielectric Margins in Insulation Components

	Minimum Margin	
Components	Switching Surge	Lightning Impulse

Coil-to-Coil	5.8	1.55
Turn-to-Turn	10.8	6.6
Oil-Barrier Space	2.6	1.75
Along the Winding	1.27*	1.17*

* The margin reduces by 20-25% in case of surface contamination with conductive particles.

It was also determined that rehabilitation, i.e., insulation cleaning and to some extent modifying the first barrier facing the winding by stabilizing the oil channel, will allow for the full restoration as well as an increase in the initial dielectric strength.

Thermal stress

Results of a temperature calculation of the winding's components are shown in Table II and in Figure 2. These examples also provide a temperature profile of the winding. Hot coils as well as hot spots were also detected. It was determined that a rise in a hot spot would not exceed 62°C when two coolers were in operation. This corresponds to the expected life of well over 45 years at an annual average temperature of 20°C [2].

TABLE II
Temperature Rise of Winding Components Above Cooling Medium

No. of	**Rise of Temperature, °C**				
Working Coolers	**Oil Average Above Air**	**Winding Average Above Oil**	**Winding Average Above Air**	**Hot Coil Above Air**	**Hot Spot Above Air**
1	37.9	23.9	61.8	68.4	75.6
2	21.4	25.5	46.9	53	61.5

Temperature Distribution along the Winding
FIGURE 2

An analysis of the cooling system's design showed the presence of a "dead" space at the top of the tank caused by a low disposition of output leading to an excessive top oil temperature at the temperature sensor. It was determined that a modification of the cooling system will lower the insulation temperature and, as a result, will prolong life.

Mechanical stress

Movement of the aluminum electromagnetic shields while under the effects of axial stress at 100 Hz was also determined to be a "weak point". The estimated force was over 30 kg while under operating conditions. This force can however exceed 150 kg while the reactor is switched on. In cases with poor or loose clamping, the shields can move and cause attrition and generation of aluminum particles.

Electromagnetic stress

It was determined that the integrated current in the electromagnetic shield can exceed 5.5 kA; however, distribution of this current through the aluminum ring can be uneven. The average density of the current is approximately 2 A/mm; however, in the current's maximum concentration zone, this density can exceed 5.7 A/mm^2. A localized elevated concentration of current may cause overheating and sparking on the surfaces especially in cases with loose shield clamping. Steps such as insulating the ring from the adjacent metallic components and properly clamping and grounding the shield can be sufficient to prevent future faults.

Assessment of busing reliability

A "weak point" of the bushing was found to be the dielectric strength of the oil channel between the bushing's core and lower porcelain. An electrical field in that channel is formed by condenser layers within the core as well as by the winding. A disposition of the bushing within the winding contributes to the formation of a large volume of stressed oil. This oil is extremely sensitive to deterioration. An analysis has shown that a reduction of the dielectric breakdown in the oil, e.g. from 70 to 50 kV, can result in a decrease of the dielectric breakdown in the stressed volume of oil by approximately ten times [3]. As a result, a change of the oil was recommended as a necessary measure. In this case, however, the customer decided to replace the bushing.

Assessment of shunt reactor condition

A failure model defined on the basis of analysis of operational experience and design reliability determined that the following diagnostic tasks should be undertaken:

- Evaluation of the insulation system condition, including:

  - detection of oil contamination and contamination of the insulation with conducting particles
  - detection of partial and creeping discharges
  - detection of excessive water content in the solid insulation.

- Evaluation of the condition of the shields as possible sources of oil overheating and particle generation.

The present insulation design was found to include winding support insulation materials with inherently high dielectric losses (tan δ = 1.5-2.0 % @ 50-60°C). Sensitivity to the detection of insulation contamination using measurements of the dielectric characteristics is therefore reduced. Correspondingly, the initial values of tan δ in the overall tests of the winding insulation were 1.0-1.7% @ 50-60°C; however, the tan δ of dry and clean insulation in the main oilbarrier space was 0.3% or less. This phenomenon will mask a change in the insulation's condition. Conversely, the oil was also suspected to be poor information medium due to a migration of particles while under the effects of an electromagnetic field and absorption of the polar decay product by the insulation's surface. As a result, partial disassembly of the core and coil, a visual inspection and testing of insulation samples were chosen as basic methods of life assessment. DP tests performed on the solid insulation samples showed a moderate degree of deterioration. A number of defects and faults was revealed such as severe contamination of the insulation especially on the pressboard sheets facing the winding which contained metallic particles, the path of discharges; overheating and electrical erosion of the aluminum shields, etc. The results of the investigation are summarized in Table III where Q, S, T and R represent the reactor phase designations.

TABLE III
Failure Modes Found in Reactors

	Reactors						
	Substation No. 1			Substation No. 2			
Failure Modes	**Q**	**S**	**T**	**R**	**S**	**T**	**Q**
Severe contamination of winding and pressboard sheets.	+	+	+	+	+	+	-
Trace of discharges along pressboard.	-	-	+	-	-	-	-
Trace of discharges between coils.	+	-	-	-	-	-	-
Overheating and electrical erosion on electromagnetic shields.	+	+	+	+	+	+	-
Mechanical attrition of aluminum shields.	+	+	+	+	+	+	-
Elevated water content (2.0-3.0%)	+	+	+	-	-	-	+
Oil leaks, wear of gaskets	+	+	+	+	+	+	+

TABLE IV
Life Extension Model

Life Extenuation Model	Refurbishment Procedure	Processing and Test Procedures
Prevention of potential faults.	Insulating, clamping and grounding electromagnetic shields. Replacement of 400 kV bushings.	Partial disassembling of the active part.
Restoration of initial margin of dielectric strength.	Replacement of the barrier sheets facing the windings. Modification of insulation structure clamping.	Overhaul of barriers. Drying, cleaning, and desludging of insulation using Regenol-spray technique. Special test program.
Reducing rate of further deterioration.	Installation of new membrane-type oil protection. Using new long-life coil. Modification of cooling system.	Desludging the active part. Endurance test of oil. Heat-run test.
Improving ability for control and protection.	Modification of electrostatic shields (separation of components, taps outside the tanks). Modification of neutral leads for transverse protection.	Special test program.
Reducing operational and maintenance costs.	Installation of long-life pumps. Provision of normal operation with one heat exchanger (with additional silicon sealing).	Measurement of losses.
Ecological benefits: prevention of oil leaks	Change of gaskets. Modification of cooling system, reduction of vibration.	Special tests and ultrasonic checks of accessories and welding. Tight-sealing and vibration of reactors.

Refurbishment Program

The life extension program consisting of refurbishment and processing and quality assurance is presented in Table IV. Additional modification details are shown in the Appendix.

Improvement of the "weak points"

The following actions were taken to correct existing and prevent potential faults:

- Insulating, clamping and grounding of electromagnetic shields.
- Replacing the barrier sheets facing the winding and modifying the oil channel close to the winding; modifying and clamping of the insulation structure.

Reducing the rate of further deterioration

The following actions were taken to reduce the rate of further deterioration:

- Installing membrane-type protection in the conservator tank to provide insulation operation with a lower oxidation medium (Figure 6, Appendix).
- Refilling with high performance oil to prevent the formation of aggressive aging products.
- Modifying the cooling system, in particular, improving the oil circulating flow (Figures 3 and 4 in Appendix).

Naphthenic-based, sulfur-free, inhibited Technol US-2000 oil was recommended. A special life test of the oil was performed in the ORGEZ Laboratory (Prague) while under the following conditions:

- Temperature at 100°C
- Copper Catalyst
- Open contact with air

The oil proved to have high oxidation resistance. There was no appearance of sludge following 2,500 hours of testing. The Neutralization Number remained at less than 0.01 mg/g KOH and the $tan\delta_{90}$ was less than 0.5%.

Improvement of control and protection

The following illustrate the steps taken to improve control and protection:

- The electrostatic shields were modified (see Figure 1 in Appendix) to provide the possibility of directly testing the dielectric characteristics of the oil-barrier space and PD testing at an operational voltage using a balance circuit.
- Modification of the neutral leads (Figure 2 in Appendix) to provide sensitive transverse differential protection of the winding.

Reduction of operational and maintenance costs

The following outlines the procedures used to reduce the costs of operation and maintenance:

- Use of new oil pumps with a bearing life of over 50,000 hours.
- Reactor operation with one heat exchanger only. Prior to refurbishment, two or three heat exchangers were utilized (summer operation).

Processing Program

The program's goal was to restore the dielectric strength margin of the insulation system by drying, cleaning and desludging the windings. The cycle-mode Regenol-spray technique was used [4]. The processing cycle consisted of a "heat wash" stage over a period of 5-6 hours followed by a "drying-filtering" stage over a period of 8-10 hours. The technological regenerative oil, Regenol, was used and contained the following characteristics: water solubility = 80 ppm @ 20°C and = 900 ppm @ 90°C, sludge solubility of 0.6%, dissipation factor of 0.3% or less @ 90°C. The induction period during the oxidation stability test exceeded 200 hours (IEC 474).

The following drying criteria were used:

- Average temperature of the insulation during the drying stage: 85 C.
- Residual pressure at finishing cycles: 0.5mm Hg or less.
- Daily rate of water removed from the cold trap of: 0.5 liters or less.
- Rise of pressure after exposing the insulation to a pressure of 0.5 mm Hg @ 85°C: 1 mm Hg per 30 minutes or less.
- Relative saturation of Regenol @ 85°C: 2% or less; water content: 10 ppm.
- Water content from the samples of pressboard: 1% or less.

The results of the drying process are presented in Table V. A typical process is shown in Figure 3. The complete treatment process took an average of 10 days (140 hours of vacuum drying in four cycles).

Drying Process of Reactor T: Cycle Heating-Cleaning - 4 hours, Deep Vacuum - 8 hours

FIGURE 3

TABLE V
Results of Drying After Refurbishment

Substa. No.	Phase	Residual Pressure mm Hg	Rise of Pressure mm Hg	Removed Water Liters	Water in Oil ppm	Water in Solid Insulation, %		No. of Cycles
						Prior	After	
	S	0.35	0.75	17.8	6.6	4.8	0.49	13
#1	T	0.37	1.00	26.2	11.0	5.7	0.50	14
	Q	0.37	1.05	26.4	4.5	8.0	0.70	14
	Q	0.34	0.50	18.6	8.0	5.0	0.541	11
#2	R	0.32	0.70	8.8	6.3	2.1	0.56	10
	S	0.34	0.50	10.8	7.8	1.3	0.62	8
	T	0.37	0.86	17.1	0.4	5.7	0.91	15

Testing and Quality Assurance Program

Temporary field laboratory

Oil sample testing that consisted of water content measurements, neutralization number and dielectric breakdown was performed in an effort to monitor the drying and cleaning processes. The paper insulation's water content was also measured in the field.

Tests to detect oil leaks

The following steps were taken to find the oil leaks:

- Testing of coolers with 3 atm air pressure, after immersing in water for one hour.
- Testing of coolers with 3 atm hot oil (about 60°C) pressure for one hour.
- Additional protection of pump terminal boxes with silicon.
- Testing of pumps with 3 atm oil pressure for one hour. Integrity of welding was verified by means of capillary-detective point.

Final test program

- Dielectric characteristics ($tan\delta$, C, R) of the main insulation spaces at two temperatures.
- Winding impedance and losses test.
- DC resistance test.
- Testing for oil leaks with 0.15 atm hot oil pressure with running pumps for three hours.
- Vibration test.
- Comprehensive oil analysis.
- PD tests at rated voltage
  - acoustical
  - electrical using balance circuit (using leads of electrostatic shields)
- Impulse tests of insulation.
- Heat Run Test at rated current with monitoring of DGA and temperature rise.

The typical dielectric characteristics of an insulation system prior to and following refurbishment are presented in Tables VI and VII. No acoustical or electrical PD signals were detected in excess of the noise level of about 500-700 pc. Because of the reactor insulation elevated sensitivity to impulse stress (Table I), a special impulse test was performed in collaboration with EGU, Czech Research Institute. The type IP-30/750 impulse generator, rated 30 kW was used. The reactor successfully withstood three impulse shocks with an amplitude of 0.7 x 1425 = 1000 kV. There were no fault gases present during the heat run test. The rise of the top oil temperature over the ambient with one cooler in operation was 10°C lower than prior to refurbishment with three coolers in operation.

TABLE VI
Dielectric Characteristics in Shunt Reactors After Refurbishment

Year of Testing	Dielectric Characteristics		
	Insulation Space	**R, MΩ**	**tan δ , %**
Factor Data 1971	HV - Ground	4000	1.0
	HV - Shield	--	--
After Refurbishment 1994	HV - Ground	12,500	0.59
	HV - Shield	63,500	0.14

TABLE VII
Characteristics of Oil in Shunt Reactor No. 975747 Prior and After Refurbishment

Oil Parameters		1989	After Refurbishment 1994	At the End of Warranty in 1996
Breakdown voltage, kV		77	74	81
tan δ , %, @ 90°C		3.4	0.19	0.06
Resistivity, Ω ·cm·10^{12}		1.7	22	120
Water content, ppm		23	8	6
Interfacial tension, mN/m		46	56	56
DGA Analysis	H_2, ppm	34	0	2.4
	CH_4, ppm	18	0	0.6
	Σ C_2H_4, ppm	54	0	1.3
	CO, ppm	240	0	25
	CO_2, ppm	3920	35	93
	O_2, %	0.43	0.16	0.16
	Total gas, %	6.9	<0.6	0.6

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BIOGRAPHIES

Victor V. Sokolov received his degree in electrical engineering from the Khar'kov Polytechnical Institute in Ukraine in 1962. In 1964 he completed a postgraduate program at the National Polytechnical Institute in Moscow with a major in Physics of Dielectric. His Ph.D., received in 1982 from Kiev Polytechnical Institute, is in the area of EHV transformer diagnostics. He started his professional career at the Transformer Research Center in Zaporozhye. Until 1990 Dr. Sokolov worked in the Installation and Maintenance Department at the Zaporozhtransformer Corporation in the area of reliability. Since 1990 he is a Technical Director of Scientific and Engineering Center "ZTZ-Service" Co. in Zaporozhye. Dr. Sokolov has published over 50 papers and is a member of CIGRE (SC #12, Transformers) and a Convenor of CIGRE Working Group #1218, Transformer Life Management.

Valery A. Shkrum received his electrical engineering degree in 1962 from the Polytechnical Institute in Khar'kov, Ukraine. After graduation, he started his professional career at the Transformer Research Institute in Zaporozhye, Ukraine. In 1971 he transferred to the Power Converter Research Institute in Zaporozhye as a Laboratory Manager. Since 1992 he is Project Manager of ZTZ-Service Co.

APPENDIX

MODIFICATION OF 400-kV SHUNT REACTOR

Prior to Refurbishment After Refurbishment

Modification of Electrostatic Shields for Separate Monitoring of Oil-Barrier Space
FIGURE 1A

Modification of Neutral Leads for Transverse Differential Protection
FIGURE 2A

Modification of Output Oil Pipes to Reduce Top Oil Temperature
FIGURE 3A

Modification of Cooled Oil Input to Reduce Oil Turbulence and
Prevent Falling Particles within Winding
FIGURE 4A

Modification of Heat Exchanger Installation to Reduce Vibration at the Cooler and Prevent Oil Leaks
FIGURE 5A

Modification of Oil-Protection System
FIGURE 6A

Modification of Pumps Installation to Improve Controls and Ability for Repairs
FIGURE 7A